STUDY ON THE USE OF FUEL CELLS AND HYDROGEN IN THE RAILWAY ENVIRONMENT

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- More information on the European Union is available on the Internet: www.europa.eu

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LIST OF ABBREVIATIONS

CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditures
CO_2	Carbon Dioxide
FC	Fuel Cells
FCH	Fuel Cells and Hydrogen
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
H_2	Hydrogen
HRS	Hydrogen Refuelling Station
NOx	Nitrogen oxides
OEM	Original Equipment Manufacturer
PM10	Organic particles between 2.5 and 10 microns in diameter
R & I	Research and Innovation
S2R JU	Shift2Rail Joint Undertaking
SU	Standard units
TCO	Total Cost of Ownership


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ABSTRACT

Fuel cell and hydrogen (FCH) technology is a promising option for replacing diesel combustion engines in rail transportation. The Shift2Rail Joint Undertaking and Fuel Cells and Hydrogen Joint Undertaking launched this study to assess the state of the art, the business case, the market potential, specific case studies and technical and non-technical barriers to the use of FCH technology in different rail applications.

This Final Study summarises the results and the main conclusions derived from the state-of-the-art, business case, market potential, case studies and barrier analysis in FCH trains in Europe.

The study shows significant market potential for FCH technology in rail. The technology provides a flexible, zero-emission and potentially cost-competitive solution to replace diesel trains. The analysis of ten selected case studies across Europe revealed attractive use cases and potential boundary conditions for FCH rail usage. Finally, several barriers were identified that have to be overcome in order to unlock the full potential of FCH technology in rail. Three targeted research and innovation (R & I) topics have been identified as the means to tackle the most important of these barriers.

EXECUTIVE SUMMARY

Europe is looking at options to replace its diesel-powered train fleet against the backdrop of climate change and the need for fast and consistent decarbonisation of the entire energy and transport system. FCH trains are well positioned to help Europe reach its greenhouse gas, air contaminant and noise-reduction goals as a versatile zero-emission technology in rail transportation. FCH technology is expected to play an increasing role in the railway sector starting with Multiple Units, especially for long-range and high-power demanding use cases. By 2030, one in five newly purchased train vehicles in Europe could be powered by hydrogen. The latest developments in the field in Germany and France[1] show that this technology will complement electrification in Europe and enable the complete decarbonisation transformation in rail with the flexibility it offers to the train operators.

FCH technology in the railway environment competes with existing drive technologies, such as diesel and catenary, but also with emerging technologies such as batteries solutions. The study shows that FCH trains perform to the rail system specifications as well as the diesel technology can. The most mature FCH application, i.e. Multiple Units, has, in addition, potential to become cost competitive with diesel-powered trains in the short term, especially where energy to produce hydrogen is cheap, as, for instance, in Scandinavia. Economically, they can outperform catenary electrification where service frequencies are low, while still providing the environmental gains of electrification. Owing to their long range and fast refuelling, FCH technology overcomes the technical constraints of batteries.

With this competitiveness of FCH technology and the given framework conditions, FCH Multiple Units can potentially replace 30 % of diesel volumes as the most market-ready application by 2030. Current Multiple Units in the market and open tenders suggest that new models can be introduced going forward, also fuelling export opportunities to non-European countries. Shunters and Mainline Locomotives follow with a relatively modest market uptake, mostly due to delayed market introduction - which is not expected to happen before 2023 - and the further need for technology development.

Across Europe, FCH train demand is expected to be primarily driven by Frontrunner markets in Central and Northern Europe that already have open and planned tenders for Multiple Units, while the Newcomer markets with a lower likelihood of deploying FCH trains are expected to energise the development of relatively new applications mostly to replace their mature diesel-powered fleets.

Based on the in-depth analysis of different case studies throughout Europe, including four case studies focusing on Multiple Units, three case studies focusing on Shunters and three case studies focusing on Mainline Locomotives, the following main conclusions can be derived for the use of FCH trains:

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[1] Alstom's new concept for an FCH variant of its Coradia Polyvalent (Régiolis) Multiple Unit

- FCH trains make economic sense above all when they are used on longer non-electrified routes of over 100 km;
- FCH trains can be used especially for last mile delivery routes, but also for main routes that have very low utilisation (up to 10 trains per day);
- Low electricity costs of less than EUR 50 /MWh and high utilisation of the infrastructure (hydrogen refuelling station, electrolyser) favour the use of FCH technology;
- FCH trains enable operation with very short downtimes of less than 20 minutes (due to fast refuelling) and are also able to withstand long operating hours of more than 18 hours without refuelling;
- FCH trains are an economically feasible clean alternative to current diesel trains in many cases;
- In some cases, battery-powered trains may appear as a more cost-effective option but come with operational constraints resulting from their highly route-specific tailored battery configurations.

FCH technology needs to take a systemic approach to the rail environment and engage simultaneously on different fronts for accelerated deployment. Due to the high dependency of economic efficiency of FCH technologies, the introduction of FCH trains is positively influenced by issues that lead to a reduction in average energy prices. Therefore the systemic use of hydrogen as an energy storage for renewable energies and the higher utilisation of H_2 infrastructure, e.g. through multimodal use of infrastructure, are particularly interesting.

The barriers this new technology faces are no different to any other novel technology on the cusp of large-scale deployment in the field of public transportation. The majority of barriers are relevant for all FCH train applications and only three of them are deemed to be high priority. Three targeted R & I projects, with an estimated total budget of EUR 113 million, can resolve these high-priority barriers in the short term. The added product availability that these technological development and demonstration projects bring will help to accelerate and optimise the successful rollout of FCH trains on a large scale.

Large-scale demonstration projects with targeted prototype and technology development projects are necessary to advance FCH trains in the future. These projects can further establish technical and economic performance specifications for commercial applications and lay the groundwork for standards and regulatory modifications. This will help FCH trains to reach their full and significant market potential in Europe and unlock the potential of FCH trains for a wider market beyond; whilst also helping Europe to reach its emissions and noise-reduction goals in rail transportation.

1. FUEL CELL AND HYDROGEN TRAINS TODAY

Despite the green image of a largely electrified railway system in Europe, 20 % of the traffic and about 40 % of the mainline network is still being served by diesel technology today[2]. In the context of climate change, where persistent and fast emissions reduction is critical, the European railway sector must do its part to contribute to the environmental transition by replacing its remaining diesel-powered fleet. Fuel cell and hydrogen (FCH) trains hold the promise of fulfilling the operational requirements of rail transport, along with the European Union's desire to reduce greenhouse gas emissions, other air contaminants and noise[3], especially where track electrification is not economically feasible. This study, commissioned by the Shift2Rail Joint Undertaking and Fuel Cells and Hydrogen Joint Undertaking, analyses the potential of the FCH technology in rail. FCH trains were found to be a versatile and viable zero-emission alternative to deliver these benefits, without sacrificing performance:

- FCH trains offer a high technical performance, with similar flexibility and versatility as diesel-powered fleets with similar range;
- FCH trains offer a reasonable economic performance and are cost competitive with diesel-powered trains where low-cost hydrogen production is possible providing zero-emission service;
- FCH trains reduce greenhouse gas emissions, air contaminants and noise levels.

The technical performance of FCH trains today indicates that FCH technology can cope with the requirements of rail transport as well as diesel trains can. In contrast to competing clean technologies like batteries, FCH technology can provide higher flexibility for operators due to the long range and high-power ratings. FCH trains can also provide a feasible zero-emission solution where service frequency does not justify high catenary electrification investments.

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[2] European Commission, 'Electrification of the Transport System', n.d.
[3] European Union, 'Transport: Connecting Europe's Citizens and Businesses', November 2014, http://europa.eu/!bY34KD.

The total cost of ownership (TCO) of FCH trains remain higher than the diesel technology in a base case scenario, despite lower maintenance costs compared to diesel powered trains. However, certain FCH train applications (e.g. Multiple Units) can already be cost competitive with diesel today in scenarios where the energy to produce hydrogen is cheap (e.g. low-cost electricity, industrial by-product hydrogen). The TCO analysis of an optimistic case shows that if the electricity price and hydrogen consumed per kilometre are lower[(4)] and the diesel price reaches EUR 1.35 per litre, FCH becomes the least costly alternative. This case reflects the current reality in some European areas like Scandinavia, where low cost electricity can power on-site electrolysis to produce hydrogen.

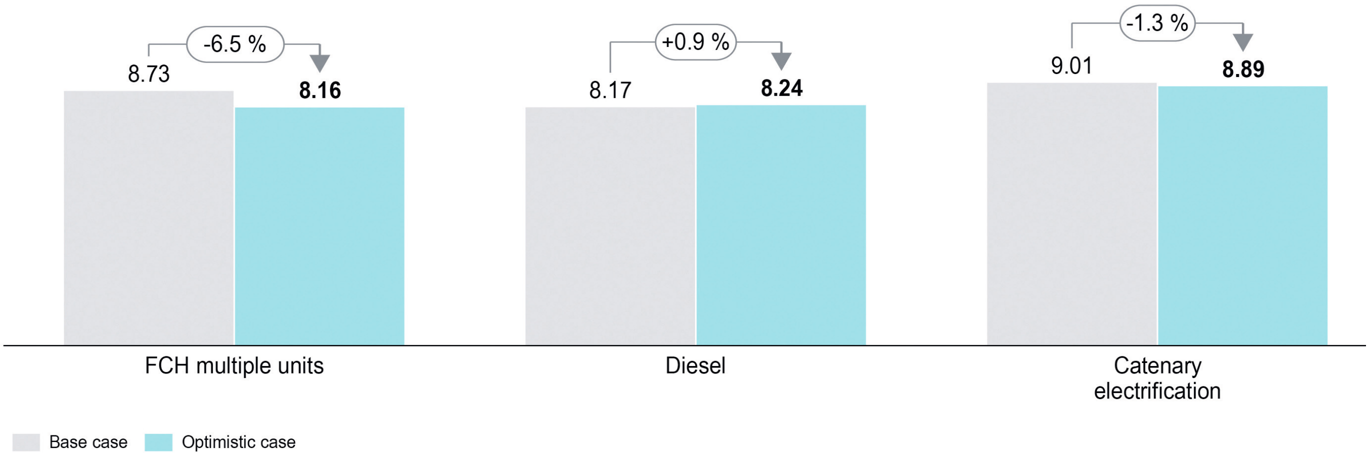


Figure 1: TCO analysis of Multiple Units in the optimistic case[(5)].

From an environmental performance perspective, FCH trains provide reductions in NOx and particulates (e.g. PM10) emissions in all case studies selected for the study. The CO_2 emissions impact of FCH trains depends strongly on the source of the hydrogen used for operation. Hydrogen produced via electrolysis from water can be the cleanest option, if the electricity is generated from renewable sources. Emissions savings depend on the carbon intensity of the electricity mix of the country in question. Alternatively, hydrogen produced from natural gas via steam methane reforming can reduce the emissions by up to 40 % compared to diesel. Assuming that the hydrogen used for the operation of the FCH trains is produced from renewable sources only, significant CO_2 emission reductions can be realised. Additionally, FCH trains mostly provide quieter operation than diesel trains, enhancing the well-being of residents and potentially increasing the value of real estate located close to the train tracks.

[(4)]Electricity price reduced to EUR 60 per MWh and H_2 consumption per kilometre reduced to 0.25 kg per kilometre.
[(5)]See Report 1 for further information on the TCO calculation.

2. MARKET POTENTIAL FOR FCH TRAINS IN EUROPE

As a viable clean and silent alternative to diesel-powered trains in Europe, FCH trains present significant market potential. The study analysed the market potential of FCH trains in European markets across three applications – Multiple Units, Shunters and Mainline Locomotives – along three scenarios[(6)] representing the low, base and high case of adoption. The market analysis revealed that FCH trains could take a market share of up to 41 % by 2030 in the high scenario. With this potential development, FCH trains could become a disruptive game changer for the remaining CO_2 emissions in the rail sector.

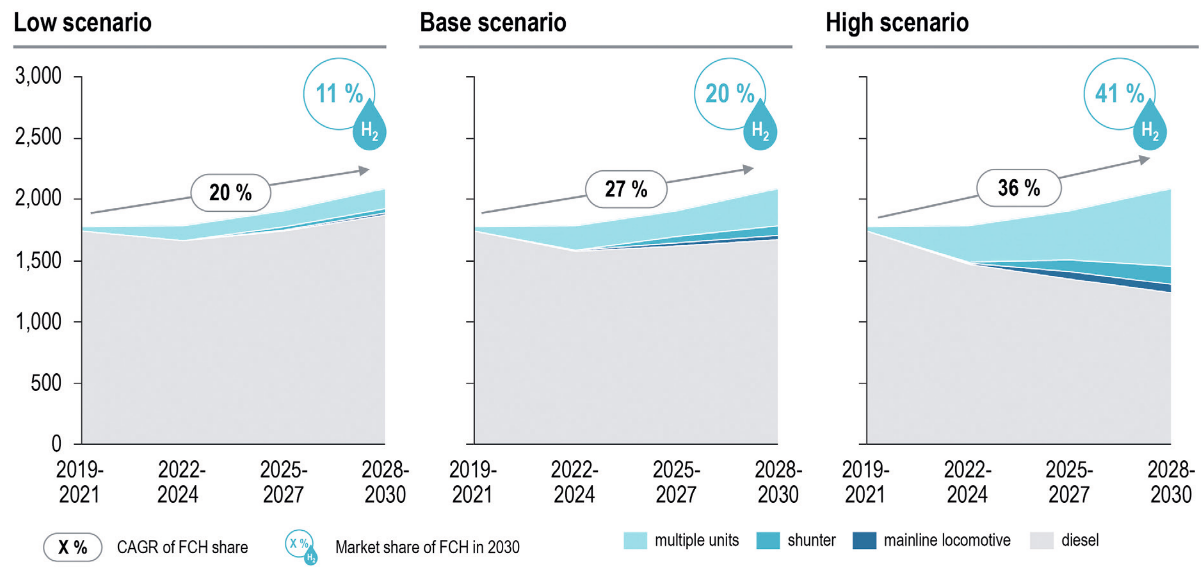


Figure 2: EU market potential for FCH trains under the three selected scenarios [standard units (SU)][(7)].

[(6)]The methodology and further detailed results are available in Report 1 of this Study (please find the links at the end of this document).
[(7)]The market potential is provided in standard units (SU), where each Shunter and Locomotive is counted as a single unit and a Multiple Unit trainset is counted per train car (e.g. 2-car vs 3-car train sets) in line with the UNIFE World Rail Market Study methodology to make the different Multiple Unit demand from different rail operators in their respective market comparable.

Under the base scenario, FCH trains are expected to take a combined market share of 20 % from diesel-powered trains in all of the considered areas of rail application in 2030. In other words, one in five of the currently diesel-powered train vehicles could be powered by hydrogen. In the base scenario, Multiple Units are the largest segment (2022-2024: 200 SU, 2025-2028: 211 SU, 2028-2030: 308 SU), followed by Shunters (2022-2024: 5 SU, 2025-2028: 50 SU, 2028-2030: 72 SU) and Mainline Locomotives (2022-2024: 4 SU, 2025-2028: 28 SU, 2028-2030: 36 SU). This constitutes a market share of 30 % for Multiple Units, 12 % for Shunters and 8 % for Mainline Locomotives of the overall purchasing volume potential in 2030 respectively and totals to 943 SU from 2022-2030.

In this case FCH Multiple Units can potentially replace 30% of diesel volumes by 2030 as the most market ready application, saving up to 305 000 t of CO_2 annually. Shunters and Mainline Locomotives relatively modest market uptake mostly stems from a delay in their market introduction which is not expected to happen before 2023.

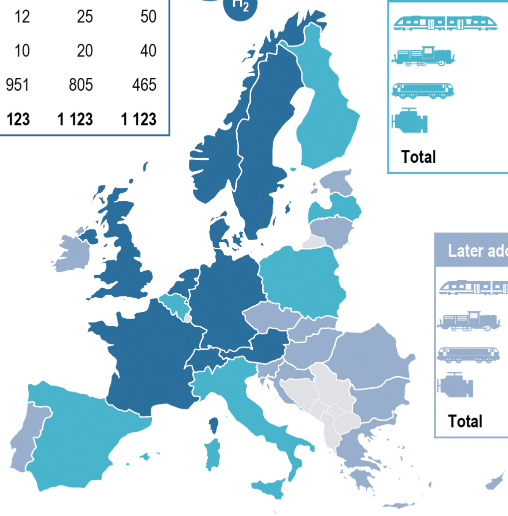
2.1. MARKET POTENTIAL ACROSS EUROPE

The study categorised European countries according to their likelihood of deploying FCH trains and replacing diesel-powered trains. The three categories are 'Frontrunner', 'Newcomer' and 'Later Adopter' markets. While in Frontrunner markets it is the Multiple Units that are driving the adoption, with ongoing project developments, planned investments and open tender procedures, in Newcomer and Later Adopter markets the Shunters are expected to play a more prominent role in demand for FCH trains. This is mostly due to the mature diesel-powered Shunter and Mainline Locomotive fleets of Newcomer and Later Adopter markets where alternative clean solutions are needed. Consequently, the market expects FCH train demand to be mainly driven by Frontrunner markets in Central and Northern Europe[8], and anticipates that the Newcomer markets will energise the development of relatively new applications (e.g. Shunters) going forward.

[8] For countries (e.g. Switzerland) that have conducive framework conditions to introduce FCH trains but low projections for diesel-powered train purchases due to an electrified fleet, a switch from electrification to FCH was considered unlikely.

Frontrunner	Low	Base	High
	150	273	569
	12	25	50
	10	20	40
	951	805	465
Total	1 123	1 123	1 123

Base 2030 28 % H_2



Newcomer	Low	Base	High
	10	21	41
	15	29	58
	4	8	17
	497	467	409
Total	525	525	525

Base 2030 11 % H_2

Later adopter	Low	Base	High
	7	15	30
	9	19	37
	4	8	15
	419	398	357
Total	439	439	439

Base 2030 9 % H_2

X % H_2 The market share of FCH train purchasing volumes – Under the base case scenario in 2028-2030

Frontrunner Newcomer Later Adopter

FCH multiple unit

FCH shunter

FCH mainline locomotive

Diesel-electric trains

Figure 3: FCH train market outlook for 2028-2030 in standard units [vehicles, train segments for Multiple Units].

Most of the global FCH train market development activities are currently concentrated in Europe, which is reflected in the state of the art, as well as the market potential analysis. This puts Europe currently at the forefront of FCH train technology, which constitutes a significant potential upside for the European FCH industry and train OEMs. They have the chance to build on their experience in Europe and export their products to emerging FCH train markets, e.g. potentially to North America and Southeast Asia in the short term and Russia, Japan and India in the medium term. If the European FCH train development is supported by R & I projects, this can help the European industry to steer and establish worldwide standards going forward. This would not only enhance the competitiveness of the European industry, but also preserve highly qualified jobs and subject matter expertise in Europe.

2.2. MARKET POTENTIAL ACROSS APPLICATIONS

In addition to looking at market potential by geography, the study examines the market potential of the three focus applications, individually. The Multiple Unit segment proves to be the most mature application whereas there is less experience and product availability in Shunters and Mainline Locomotives.

As the most mature segment, Multiple Units are expected to have the highest market potential replacing up to 30 % of diesel volumes by 2030. Short-term and tangible product availability is the strong driving force behind these numbers. Current models offer sufficient space for hydrogen technology (fuel cell, cooling system, batteries, and hydrogen storage) and concrete project demand from the first tenders for Multiple Units suggests that new models can be introduced.

In contrast, FCH Shunters enjoy a relatively small market demand mostly due to the fact that they are still at an early market stage and the technology requires further development. A lack of prototype testing and the consequent lack of products to act as showcases in a railway environment lead rail operators to be more conservative in their projections for this segment.

Likewise, FCH Mainline Locomotives are currently experiencing a similar barrier to FCH Shunters. There too, the market potential is dampened by a lack of available products. The strong cost competition from trucks in the logistics sector is often cited by market participants as hindering the development efforts in respect of zero-emission alternatives to diesel-powered locomotives.

Additional market potential for the Shunter and Mainline Locomotive segments could potentially be unlocked with increased product availability. Therefore, this market segment could especially benefit from further R & I efforts.

3. CASE STUDIES TO SHOWCASE FCH IN THE RAILWAY ENVIRONMENT

An analysis of 10 different case studies[9] focusing on Multiple Unit, Shunter and Mainline Locomotive applications throughout Europe identifies key learnings for the use of FCH technology in rail application.

- FCH trains are cost-competitive when designed for long non-electrified lines over 100 km in length;
- FCH trains are especially viable for main routes with very low utilisation (maximum 10 trains per day) but also for last mile transport;
- High hydrogen infrastructure utilisation (hydrogen refuelling station, electrolyser) and low cost electricity (less than EUR 50/MWh) provide favourable conditions for the FCH technology;
- FCH trains are characterised by relatively fast refuelling resulting in less than 20-minute downtimes and can be operated for more than 18 hours without refuelling.

Flexible levels of hybridisation (ratio between fuel cell and battery power) make the FCH trains applicable for a wide range of use cases. Hybridised FCH trains feature, for example, high loads of up to 5 000 t, high speeds of up to 180 km/h and long-distance travelling of up to 700 km. Although many case studies have specific route conditions, the trains designed for these conditions should be able to operate in a wider fleet based on various routes with different profiles. This flexibility has to be considered in order to define the right level of hybridisation, e.g. the ratio between fuel cell and battery power or the adequate tank volume for carrying the hydrogen.

[9] In the following chapters, 9 of the 10 case studies are analysed in more detail. The purely theoretical case study Romania will not be described in this report. Details can be found in Report 2. Assumptions made in this case study are based on theoretical calculations, only and there is no direct comparability with the other case studies.

3.1. MULTIPLE UNIT CASE STUDIES

Multiple Units are widely used for passenger transport in Europe today. In many densely populated areas, Multiple Units are powered by electricity from a catenary system, especially if the trains are operated regularly at high frequency. On less frequently used routes, mainly diesel-powered Multiple Units are used to serve remote locations, for instance those in mountainous or rural areas. FCH Multiple Units can replace diesel-powered trains and provide a zero-emission option.

The train configuration will typically be tailored towards the specific route and the country of operation. A flat route profile combined with a large distance between different cities would result in a train design with high maximum speed and rather low maximum tractive effort, whereas for a route with a strong elevation profile, a higher average power would be needed. The required passenger capacity defines the number of rail cars to be used, usually between two and four.

In order to demonstrate the impact of different train configuration and route profiles on the environmental and economic performance, three selected case studies have been analysed.

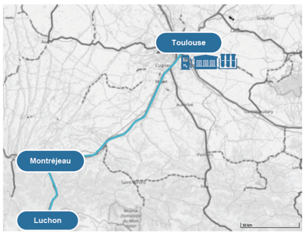
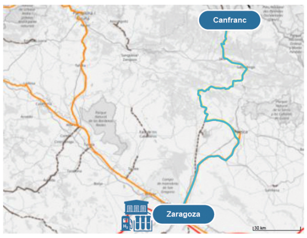
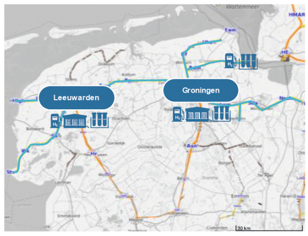
Multiple unit case studies	Montréjeau – Luchon, France	Aragon, Spain	Groningen & Friesland, Netherlands
Overview of route specifications			
Track length	140 km	165 km	300 km
Rolling stock	3x 4 car trains (bi-mode)	2x 4 car trains (bi-mode)	70x 3 car trains
H_2 consumption	0.36 kg/km	0.31 kg/km	0.22 kg/km
	245 kg/day	240 kg/day	16,500 kg/day
Total CAPEX	EUR 25 m	EUR 14 m	EUR 398 m
Characteristics	Partly electrified route with a low utilisation on 36 km	Cross border connectivity and long route without electrification	Fast trains for intercity connections
Total cost of ownership [EUR/km_{train}]			
Diesel	18.5	9.3	4.8
FCH	**21.2**	**12.4**	**5.0**
Catenary	27.5	22.6	4.5
Battery	19.9	13.7	5.3
Environmental analysis			
CO_2 savings [tons per year]	1,334 t	767 t	56,389 t

Figure 4: Overview of the Multiple Units case studies including economic and environmental results.

In the case of Montréjeau-Luchon (France), a 140 km route was investigated in which a bi-mode train is operated over 36 km with FCH and 104 km is operated using the existing catenary system. The train takes passengers from Toulouse to the Luchon mountain region via Montréjeau. To supply the FCH train with hydrogen, an HRS would have to be set up in Toulouse, which would be supplied with hydrogen by an on-site production facility. Due to the relatively low utilisation of the line with three trains and the relatively short distance without electrification, a bi-mode train with battery drive would be a possible alternative.

In Spain, a closer look was taken at rail transport in the Aragon region. For the calculation of the TCO, a route was selected which, in contrast to the French case study, has a lower share of route electrification. Overall, compared to diesel vehicles an extra cost of approximately EUR 3/km comes into the TCO calculation, but FCH technology is the cheapest clean alternative investigated in this specific case.

FCH technology is considerably more economical when operating longer distances and using a larger number of FCH trains that are supplied by a central hydrogen refuelling infrastructure, as in the Netherlands case study. Here, passenger transport was investigated in the regions of Groningen and Friesland. Compared to diesel technology, there is only a 4 % cost premium for the FCH train that can provide a zero-emission rail service. In this case, higher utilisation also serves to increase the competitiveness of the catenary option. However, the longer development timelines for the catenary installation may be prohibitive for stakeholders seeking to quickly capture environmental benefits.

MAIN TAKEAWAYS FOR MULTIPLE UNITS

Overall, the investigated case studies showed that FCH Multiple Units are a viable clean alternative to existing diesel Multiple Units. FCH powertrains for Multiple Units exhibit promising economic and ecological advantages. Their routes are usually connected to a main traffic junction, which has the necessary infrastructure for the on-site production of hydrogen. The use of FCH technology seems to be especially economical for a dense, non-electrified network with average utilisation by trains that also reach out to more rural or mountainous areas. The FCH technology can also offer advantages for cross-border operation as it can be operated independent of catenary voltage level, which differs in many countries. For Multiple Units, the TCO premium for FCH technology compared to diesel technology was calculated at between 4 % and 35 %. The switch to a more environmentally friendly technology can result in an average CO_2 emission reduction of 550 t per year per Multiple Unit train set.

3.2. SHUNTER CASE STUDIES

Shunters can be used across a wide range of use cases with operating conditions varying widely. Shunters are often used to transport wagons or locomotives between different terminals, travelling over distances of several kilometres. Therefore, performance parameters need to be defined depending on the use case specific load to be moved and the distance to be covered.

Shunters can be defined by their power ratings range: up to 110 kW, between 110 kW and 250 kW, and above 250 kW. When it comes to FCH technology, the most powerful Shunters for longer distances are the most relevant. Shunters powered by batteries provide better cost performance for low-range shunting operations with long idle times and can also provide a clean solution if powered by renewable electricity.

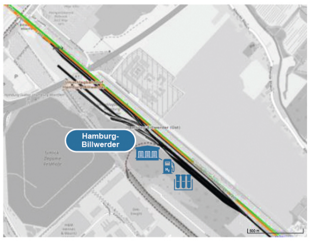
Shunter case studies	Hamburg-Billwerder, Germany	Riga Node, Latvia	Gdansk, Poland
Overview of route specifications			
Track length	10 km	100 km	35 km
Rolling stock	15 Shunters	15 Shunters	10 Shunters
H_2 consumption	0.39 kg/km	0.49 kg/km	0.72 kg/km
	480 kg/day	850 kg/day	180 kg/day
Total CAPEX	EUR 40 m	EUR 29 m	EUR 21 m
Characteristics	Shunting yard in a large urban area and next to Hamburg port	Shunting operation between several port terminals	Marshalling yard in collocation of the refinery supplying hydrogen
Total cost of ownership [EUR/km_{train}]			
Diesel	10.1	20.9	32.1
FCH	**12.9**	**20.4**	**36.7**
Catenary			
Battery	11.7	21.8	36.9
Environmental analysis			
CO_2 savings [tons per year]	1,969 t	3,350 t	339 t

Figure 5: Overview of the Shunter case studies, including economic and environmental results.

Shunters can be operated for over 50 years if maintained well. Therefore, the initial CAPEX investment is spread over a very long lifetime. In order to keep the Shunters operational, they will be refurbished over time to meet the latest requirements for emission standards and power performance. FCH technology can be an attractive option for retrofitting existing Shunter fleets, as both space requirements and weight can be managed.

Three case studies were selected for the investigation of FCH train applications in the field of Shunters.

Hamburg-Billwerder has one of the most modern terminals in Germany linking train traffic with road traffic. Being on the main artery from Berlin to Hamburg and close to the port of Hamburg, Shunters are not only on the move within the terminal but also in the adjacent rail network. FCH technology exhibits an additional cost of EUR 2.8/km TCO in comparison to diesel. In this specific case, battery trains could be the cheaper option owing to the high idle time of the Shunters used.

In Riga, the Shunters have to cover distances of up to 200 km per day with high loads as they travel between different port terminals. The fleet has already been significantly modernised and retrofitted with powerful engines. In this case, FCH technology represents the most attractive zero emission option. FCH Shunters can provide similar performance to diesel Shunters but provide savings during the Shunters' idle times, which are still high. At the same time, battery trains also represent an alternative means to achieve zero emissions for rail, but they could face problems if they were required to deal with high demand.

The third case study that was investigated for the application of Shunters is in Gdansk. Here, Shunters are predominantly used to carry the chemical products of the adjacent refinery. In this case, the location offers the possibility to supply the FCH Shunters with hydrogen from a by-product stream from the refinery. This source could become highly cost competitive, as soon as a certain threshold of H2 offtake can be reached due to the employment of several FCH Shunters. This will increase the utilisation of the H2 infrastructure and therefore lead to an increased cost-effectiveness. However, in the currently anticipated use case, the low daily mileage of the 10 FCH Shunters requires a relatively high investment in infrastructure.

MAIN TAKEAWAYS FOR SHUNTERS

FCH Shunters are particularly profitable if they are operated with a low idle time and over longer distances. As Shunters are usually operated within a defined radius and always return to the main shunting yard, the infrastructure to be built for hydrogen refuelling can be optimally utilised. The use cases for Shunters differ widely. In the case studies, it was found that operators require Shunters to offer high flexibility (e.g. the capability to serve as a Mainline Locomotive for freight transport over 200 km), which, in comparison to other clean technologies (battery or catenary), can be served particularly well by FCH technology. In addition, there is considerable potential for a multimodal approach, operating Shunters close to interfaces with other modes of transportation. Increasing the utilisation of the hydrogen infrastructure would be conceivable, for example, by also supplying Mainline Locomotives, trucks or ships. For Shunters, a TCO premium for the FCH technology compared to diesel technology was calculated at between 0% and 28%. The switch to a more environmentally friendly technology can result in an average CO_2 emission reduction of 130 t per year per Shunter.

3.3. MAINLINE LOCOMOTIVE CASE STUDIES

Mainline Locomotives are used for passenger and freight transport and operate mostly on major routes. In Western Europe, many catenary-electric Mainline Locomotives are used due to the high level of electrification within the network. However, diesel-powered locomotives are in use for international freight transport. Furthermore, freight last mile delivery constitutes an area that is operated by diesel locomotives, often combined with Shunters for the final distribution of the freight. Another reason why diesel-powered trains are used is rail track congestion. The congestion in Central Europe makes the use of non-electrified locomotives more attractive as they can also operate flexibly on less congested non-electrified routes. Moreover, this flexibility can be used to reduce Rail Track Access fees, as the most economical route option can be chosen if fewer route constraints exist.

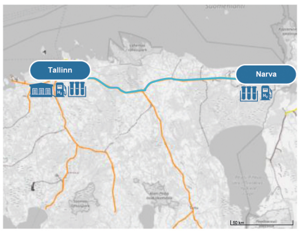
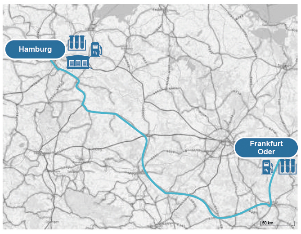
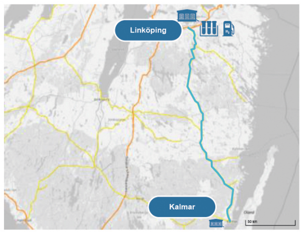
Mainline locomotive case studies	Tallinn – Narva, Estonia	Frankfurt (Oder) – Hamburg, Germany	Kalmar - Linköping, Sweden
Overview of route specifications			
Track length	210 km	720 km	230 km
Rolling stock	2 Locomotives	5 Locomotives	5 Locomotives
H_2 consumption	0.67 kg/km	0.82 kg/km	0.48 kg/km
	670 kg/day	1,500 kg/day	3,000 kg/day
Total CAPEX	EUR 14 m	EUR 38 m	EUR 48 m
Characteristics	Cross-border operation between Russia and Estonia	Long range freight transport from border to port	Passenger and freight transport between two cities
Total cost of ownership [EUR/km$_{train}$]			
Diesel	22.6	9.2	5.7
FCH	**22.8**	**11.9**	**6.7**
Catenary	24.4	6.4 [10]	22.0
Battery			
Environmental analysis			
CO_2 savings [tons per year]	2,556 t	12,874 t	4,980 t

Figure 6: Overview of the Mainline Locomotives case studies including economic and environmental results[10].

Mainline Locomotives feature very high maximum and average power ratings. A high constant power output is required to cope with the heavy weight of trains and the demanding route profiles. Most of the time, freight wagons limit their speed and account for the highest noise emissions within the entire system.

[10] In the case of infrastructure investment costs (catenary), the possible overall utilisation of the route or sections of the route by other trains (not related to the case study) is considered. This reduces the investment costs that are allocated to the train TCO. For the case Frankfurt (Oder)-Hamburg, Germany, this means a reduction in electrification costs of approximately 80 %.

FCH train applications are a good alternative for three reasons: They can achieve similar performance as existing technologies, they guarantee operational capability across national borders, and they offer a high level of flexibility in respect of route guidance. The substantial investment costs associated with electrification can often not be justified, especially if main lines feature low utilisation.

Within the scope of Mainline Locomotives, three different case studies were considered. The first case study examines a route covering a distance of 210 km in Estonia. The route connects the capital Tallinn with Narva at the Russian border, where a cross-border connection would also be conceivable. The route's elevation profile is very flat. Due to the relatively low utilisation of the line and the favourable electricity prices, as well as the lower maintenance costs for FCH Mainline Locomotives in comparison to diesel, the FCH technology represents the most favourable option for the operation of the line.

A German case study investigates an alternative route between Frankfurt (Oder) and Hamburg. Due to the lack of electrification, this route cannot be used as a regular alternative to the heavily used Berlin-Hamburg route. At the moment, only diesel locomotives have enough flexibility to use this secondary line continuously. A clean alternative would be desirable in order to avoid the CO_2 emissions. In this case, the analysis of the TCO shows that catenary trains could be a favourable alternative to FCH trains. It must be noted that this would only be the case with high capacity utilisation of the secondary route, i.e. if all trains that used this route were powered by catenary electricity. Otherwise, FCH trains could be an attractive alternative if the trains that used the route were only to be replaced successively.

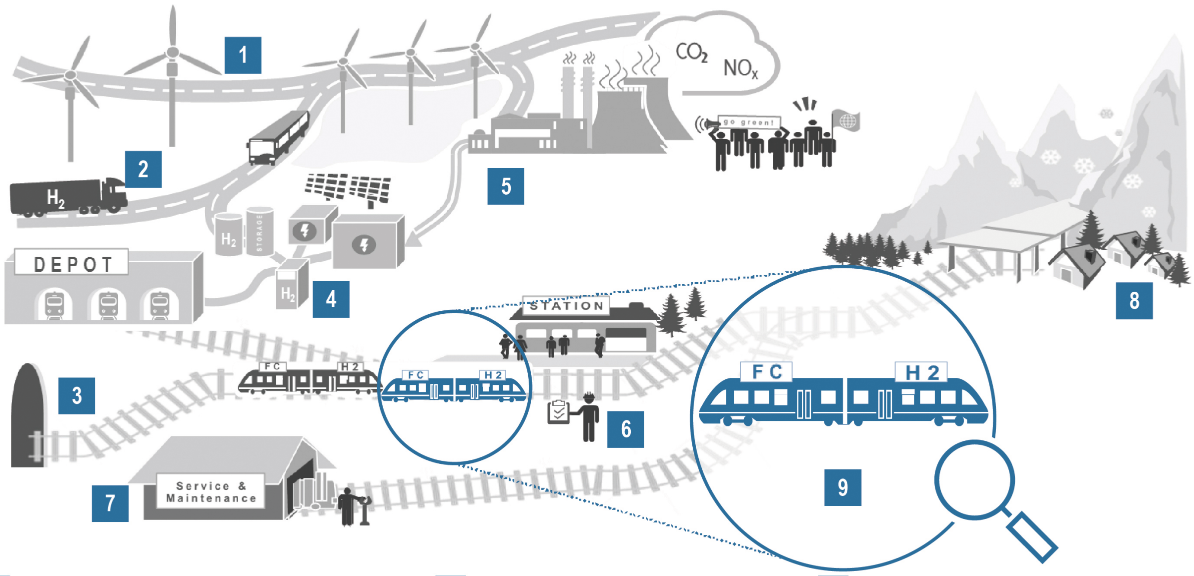
A 230 km long non-electrified line between Kalmar and Linköping is examined in the Swedish case study. Calculations are based on the use of five Mainline Locomotives for passenger and freight transport on the route. The required HRS with on-site hydrogen production via electrolysis is located in Linköping. The electricity can be sourced from hydropower or nuclear power plants, which provide the majority of electricity in Sweden. Due to the low utilisation of the line, the use of FCH technology, which is EUR 1/km more expensive than the currently used diesel-powered technology, can be an attractive zero-emission alternative that comes at a small TCO premium. Furthermore, with rising oil prices, FCH trains could become cost competitive under the specific assumptions taken in this case.

MAIN TAKEAWAYS FOR MAINLINE LOCOMOTIVES

The case studies indicate that FCH technology provides the only fully flexible, zero emission powertrain option for Mainline Locomotives. Today, however, FCH Mainline Locomotives are not commercially available on the market and the case study analysis was conducted based on conceptual design. Going forward, the special circumstances of freight transport by rail must be taken into account. Freight trains are not only operated on fixed routes but are used across the entire rail network within a country or even beyond national borders. As Mainline Locomotives have long life expectancies, retrofitting options for the powertrain also have to be considered. Furthermore, new hydrogen storage options have to be developed to facilitate a successful market introduction. In order to strengthen the economic use of Mainline Locomotives in the rail environment, respective products will need to be developed via targeted R & I activities. For Mainline Locomotives, a TCO premium for the FCH technology compared to diesel technology was calculated at between 1 % and 30 %. The switch to a more environmentally friendly technology can result in an average CO_2 emission reduction of 1 620 t per year per Mainline Locomotive.

3.4. OVERVIEW OF FOCUS TOPICS DISTILLED FROM THE CASE STUDIES

The analysis of the case studies shows promising potential for the FCH technology. At the same time, the interaction with rail stakeholders identified various focus topics to learn from for any future FCH train deployment project. The overview below highlights the topics that either constitute optimisation potential for projects or are potential barriers to implementation that can be circumvented if addressed appropriately early on. The focus topics need to be considered for a successful introduction of FCH technology in the railway environment.



1 Renewable H_2 generation via electrolysis
2 Multimodal approach with buses/trucks/etc.
3 Interoperability with other infrastructure
4 H_2 refuelling station
5 Industrial H_2 supply
6 Regulations and permitting
7 Service and maintenance requirements
8 Safety/public acceptance of H_2 technology
9 Technical requirements

Figure 7: Schematic representation of FCH train eco-system including selected focus topics.

1. Renewable H_2 value chain

Significant progress has been made over the last few years on global decarbonisation commitments, with a clear trend towards more ambitious targets and initiatives to limit greenhouse gas emissions and other air pollutants. Fuel cell and hydrogen technologies can play a crucial role in the transition towards a low-emission future via renewable hydrogen produced by electricity from renewable energy sources. Europe has already showcased hydrogen generation assets. However, these assets have not been deployed at the multi-MW scale necessary to power large FCH train fleets. As the cost of hydrogen is closely interlinked with the cost of the electricity used to generate the hydrogen, the sourcing and pricing of electricity as well as the asset utilisation levels of power-to-gas plants should be carefully considered in any efforts to ensure a renewable H2 value chain. It should be noted that the high asset utilisation requirement of hydrogen production assets can tie in well with the long-term planning orientation of a railway environment. Offtake agreements can provide highly valued demand and cost security to both the renewable hydrogen producers and the rail operators.

2. Multimodal approach

Hydrogen is an enabler of various applications and can thus provide the necessary interlinkage with various sectors and end user needs. In the context of FCH trains, this means that other modes of transport in the same geographical area, e.g. FCH buses or fuel cell electric vehicles, could be powered by the same hydrogen production and refuelling stations as the trains. Sharing the infrastructure has the potential to increase the utilisation rates of these assets and consequently decrease operating costs, ultimately benefiting the users. While the multimodal approach has the potential to decrease costs, it can end up increasing the complexity and interdependency of the system. It therefore calls for careful planning and execution. Cities such as Groningen in the Netherlands can provide an example of how, through long-term planning, an economy relying entirely on FCH technology can be envisioned, covering the entire value chain.

3. Interoperability with other infrastructure

Interoperability of FCH trains with other infrastructure has implications for the overall transport system in Europe. All parts of the rail infrastructure, including bridges, tunnels, rail tracks, roads, stations, platforms, depots, catenary electrification, etc., must function cohesively. In order to ensure that FCH trains are incorporated into this system as seamlessly as possible, certain safety protocols, product standards and regulations will need to be re-evaluated in line with the unique considerations that come with hydrogen. For example, if hydrogen stored on the roof of FCH Multiple Units leads to changes in train dimensions, then issues with clearance and potential interactions with any overhead electrified catenary wiring must be considered in advance. Similarly, any area of the rail infrastructure where hydrogen could potentially become trapped would need examination. However, for some infrastructure, existing standards and requirements for on-board transportation of hazardous materials may already be in place. As with all alternative technology powered trains, different stakeholders in the railway environment will need to work together for FCH trains to function smoothly. In many European countries, the owners and operators of rail infrastructure do not own or operate the trains. In such cases, the train operator needs to procure the FCH trains, the energy provider and infrastructure operator need to develop the hydrogen production and refuelling infrastructure, and the station operator needs to invest in hydrogen sensors and ventilation systems. Finally, it should be noted that FCH technology can also advance rail interoperability through the flexibility of the technology. FCH trains can enhance cross-border transportation where interoperability of differing electrical systems has not been achieved or on routes where electrification is not possible. FCH trains can also provide rail transportation to those communities living in protected areas, where emissions are prohibited.

4. H_2 refuelling infrastructure

Hydrogen as a fuel is dispensed through infrastructure called hydrogen refuelling stations (HRS), which are used for various mobility applications. Although in the case of FCH trains they typically need to be designed to satisfy certain specifications, i.e. they must have enough capacity to supply the fleet at peak consumption, HRS is already a proven technology. About 200 HRS are in use in Japan, Europe (Germany) and the United States (California) for other mobility applications. Therefore, the industry is confident that FCH trains can be supplied with hydrogen safely and reliably. For cost optimisation, it is important for HRS to be built to strictly foreseeable capacity requirements. Unnecessary over-capacity should be avoided if no short-term expansion of the fleet is planned, to prevent under-utilisation and associated TCO increases per train. Gradual expansion of the HRS infrastructure is already possible today owing to modular solutions that can integrate additional storage and compression equipment as an FCH fleet grows. These advances make it possible for HRS to be tailored to the requirements of specific use cases, optimising cost considerations and increasing performance along the value chain.

5. Industrial H_2 supply

Certain industries such as oil and gas refining, chlorine, fertiliser or steel production, methanol synthesis and glass manufacturing produce hydrogen in their production processes. When this hydrogen cannot be used further, it ends up being burnt to produce heat or simply discarded through flaring. Utilisation of such excess hydrogen as fuel for FCH trains could provide optimisation opportunities, both in terms of hydrogen cost and to some degree emissions, since CO_2 emissions can be reduced by more than 30 % in comparison to burning fossil liquid fuels. To maximise benefits, hydrogen fuel production and consumption should happen at the same location, and any additional required investments, e.g. to purify hydrogen for use in fuel cells, should be justified by the fuel consumption volumes of FCH trains.

6. Regulation and permitting processes

Rail regulations need to be adapted to allow for the introduction of FCH technology, and current FCH relevant regulations need to be expanded to cover aspects specific to rail applications. Before FCH trains can be operational, permitting procedures at both European and national level need to be in place. Furthermore, land use plans need to be finalised for any related infrastructure, e.g. HRS, in line with local regulations. Finally, safety regulations at the European and national level need to be followed and any international standards regarding fire safety need to be respected.

7. Service and maintenance requirements

Service and maintenance requirements of an FCH train will be similar to those involved with electric or diesel train maintenance, except for the powertrain related components and hydrogen storage tanks. In addition to the rolling stock, service and maintenance requirements of FCH related infrastructure, e.g. electrolysers, HRS and modifications to existing train maintenance workshops, should also be considered. Despite the required initial investments, including the retraining of maintenance staff, experts indicate that owing to the design features of FCH powertrains, FCH trains will have lower service and maintenance requirements and costs compared to diesel technology in the long run.

8. Safety concerns of local community

Novel technologies in public transportation typically receive a vast amount of public scrutiny. For FCH trains, the situation is no different. Communities in close proximity to FCH relevant infrastructure will raise questions about the safety of FCH technology. Projects such as HySafe, HyApproval and HyTrust have already made headway in providing the public with more information and guidelines on issues of flammability, leakage and handling of hydrogen. But ongoing engagement with local communities is still necessary for every project, especially for developments in densely populated urban areas. Engaging with the local communities consistently alongside other stakeholders can de-risk the project by moderating their concerns. Therefore, a well-defined and executed stakeholder management strategy is crucial to the success of early FCH train development projects.

9. Technology specifications (fuel cells, hydrogen tanks)

FCH technology has certain technology specifications that need to be carefully considered in the design process. Depending on the type of fuel cell used in a fuel cell system, several extra components might need to be part of the powertrain. Driven by the performance requirements of a specific use case, these components may ultimately demand too large a space, thereby complicating the implementation. Fuel cells can be complemented by batteries for use cases where power requirements are variable. With the correct design of a battery based on a defined use case, the cost of fuel cells can actually be reduced through such hybridisation. It is important to note that hydrogen tanks have certain limitations in terms of connectors and currently have to be placed in the same train segment as the fuel cells, which negatively influences the refuelling process.

4. RECOMMENDATIONS FOR A SUCCESSFUL IMPLEMENTATION OF FCH TECHNOLOGY IN THE RAIL SECTOR

Fuel cells and hydrogen are highly promising technologies that can play an essential role in the shift towards a low-emission world. The challenges FCH currently faces in the rail sector mainly stem from FCH being a new technology that needs initial support to unlock its full potential. However, none of the identified barriers are deemed to be show-stoppers. As with any new technology, there are multiple options that can help to accelerate and optimise the successful roll-out on a large scale. A set of three targeted research and innovation (R & I) projects could directly address a majority of the identified barriers provided that the scope and available budgets are aligned.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4.1. BARRIERS TO THE WIDESPREAD ADOPTION OF FCH TECHNOLOGY IN RAIL

The chart below summarises the 31 barriers this study has identified, consisting of 21 technological and 10 non-technological barriers to the adoption of FCH technology in the railway environment. Close to 80 % of the barriers, including all the high-priority ones, relate to all FCH rail applications, i.e. Multiple Units, Mainline Locomotives and Shunters. By quickly addressing especially the three high-priority barriers through short-term R & I, FCH technology can be positioned for a successful implementation in the rail sector. With the correct scoping and objective setting for the suggested short-term R & I projects, a large number of barriers can be addressed simultaneously.

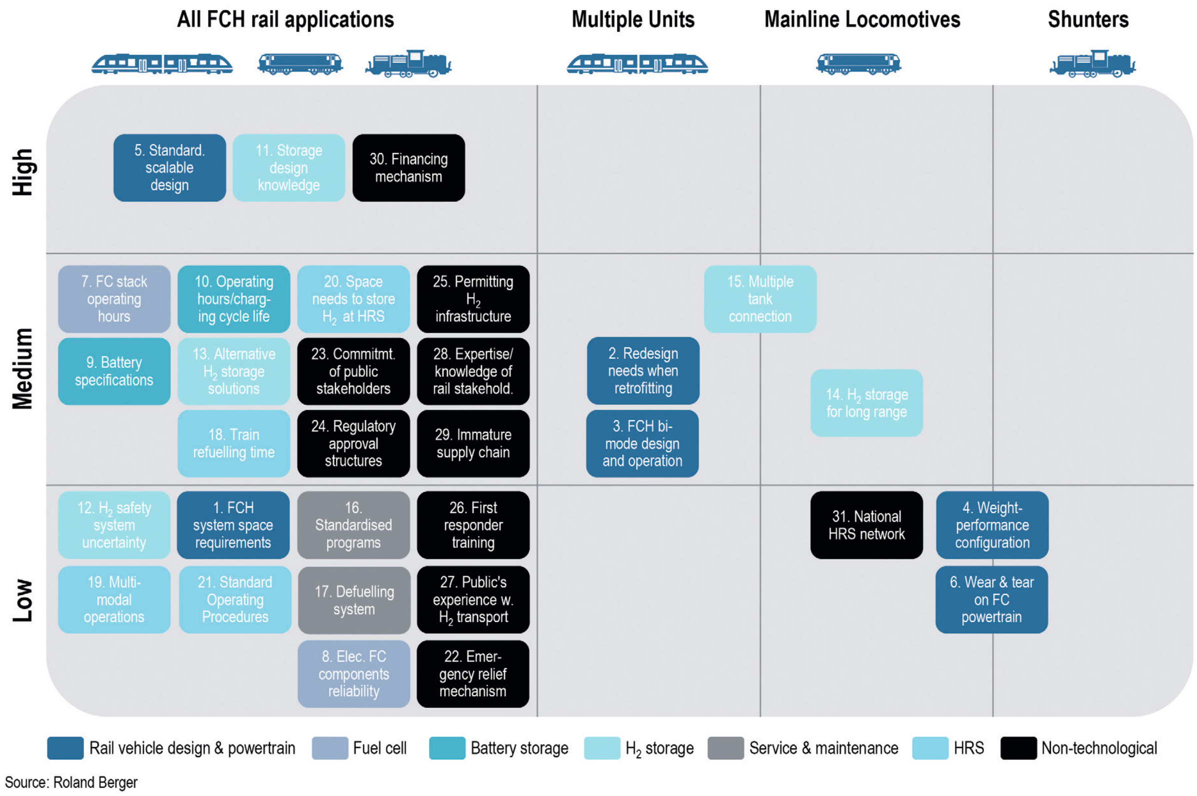


Figure 8: Barriers clustered per FCH train application and priority for short-term R & I.

Most of the remaining technological barriers constitute optimisation potential to enable FCH technology to better match or even outperform diesel or electric trains. They will need to be gradually resolved to increase the competitiveness of FCH trains in the market. Most of this optimisation potential relates directly to the FCH train itself, but the hydrogen refuelling infrastructure and service and maintenance system also have scope for improvement.

Beyond the technological aspect, the identified non-technological barriers are mainly driven by a lack of experience, knowledge and specific framework conditions for FCH technology in the rail environment. For example, utilising exceptional regulatory approval structures for FCH trains results in more cumbersome processes. Standardising such approval processes would reduce time delays and associated additional costs by decreasing the complexity of the implementation. The figure below provides an overview of technological and non-technological barriers in the railway environment.

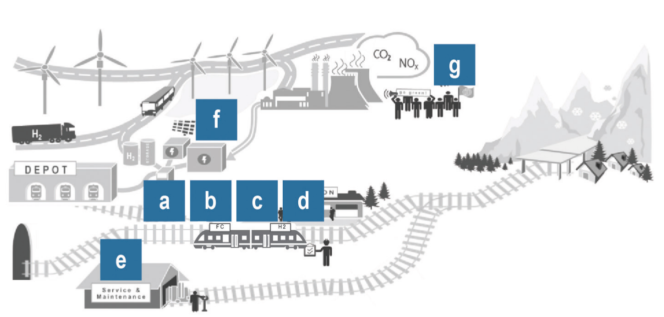
Design & Engineering (a)
1. Addditional space required by FCH system in new designs
2. Potential structural changes and redesign requirements in retrofits
3. No available designs and safety concerns for FCH bi-mode operation
4. Reduced train performance due weight characteristics changes
5. Limited experience with designing standardised, scalable, customisable powertrain
6. Wear and tear on FCH powertrain fom rail operations

Fuel cell (b)
7. Fuel cell stack operating hours
8. Reliability of electronic FCH components in rail applications

Battery storage (c)
9. Limited expertise in battery specifications
10. Battery sufficiency (oper. hours / cycle life)

Maintenance (e)
16. FCH rail and maintenance programs
17. Rail H_2 maintenance defuelling system

Non-technological (g)
23. Commitment of public stakeholders
24. No efficient / appropriate regulatory structures
25. Lack of permitting process for rail H_2 infrastructure
26. Lack of first responder training for FCH rail accidents
27. Limited public experience with H_2 technologies in transport
28. Limited rail stakeholder knowledge about FCH technologies
29. Immature FCH rail supply chain
30. Insufficient financing mechanisms supporting FCH trains
31. Complex build-up of hydrogen refuelling infrastructure



Hydrogen storage (d)
11. Lack of knowledge designing onboard H_2 storage systems
12. Uncertainy on effective vehicle H_2 safety system
13. Optimisation potential via alternative H_2 storage solutions
14. Missing solutions for H_2 storage in Mainline Locomotives
15. Lack of solutions to connect tank systems across train cars

Hydrogen refuelling station (f)
18. Refuelling time requirements for large amounts of hydrogen
19. Limited experience with Multi-modal operation of HRS in the rail environment
20. Large space and storage requirements of HRS
21. Missing FCH infrastructure Standard Operating Procedures
22. Lack of experience with emergency relief mechanisms of FCH system

Figure 9: Barriers to FCH technology in the railway environment.

4.2. RECOMMENDED R & I PROJECTS

Based on the analysis conducted, there are three particular topics that should be addressed before FCH trains can be introduced to the rail market. Specifically, these are:

- Large-scale demonstration of Multiple Unit train fleets;
- Development, engineering and prototype operation of Shunters or Mainline Locomotives;
- Technology development for optimised hydrogen storage system for FCH rail applications.

The three high-priority topics can be addressed through three tailored R & I projects described in the figure below. Alongside the high-priority topics, selected medium and low-priority topics to market introduction should be included within the same project to maximise their impact for commercialisation. The project design ensures that the relevant high-priority topic is directly addressed, while the low and medium priority topics are tackled within their respective work packages, complementing the overall objective.

	A Large-scale demonstration of Multiple Unit train fleets	B Development, engineering and prototype operation of Shunters or Mainline Locomotives	C Technology development for optimised hydrogen storage system for FCH rail applications
High-level project scope	10 - 15 1 – 2	5 - 10 1 – 2	H_2
Objectives of project	> Large scale demonstration project of 15 or more Multiple Units could enable the first fleet sized FCH train deployment	> Development and implementation of five new FCH Shunters or Mainline Locomotives (or ten retrofits), including concept design, engineering, and prototype	> Integrated technology development project for optimised hydrogen storage including analysing; filling pressure, tank location, cross-car connections, etc
Est. budget before funding	EUR 80 – 100 m	EUR 15 – 20 m	EUR 4 – 7 m

Figure 10: Overview of short-term R & I project to investigate relevant topics.

The large-scale demonstration of a Multiple Unit train fleet project can mobilise[11] the required funding for an initial deployment of up to 15 trains that will ideally be supplied by a single large-scale HRS to achieve economies of scale. This project can prove the potential of the FCH technology at scale, increase operational and commercial experience around FCH trains and be the platform through which FCH train specific financing mechanisms are developed and established. The second suggested R & I project can address the lack of FCH technology knowledge, including the lack of Shunter and Mainline Locomotive specific experience, by developing new FCH Shunters/Mainline Locomotives, or retrofitting them. It will close the current product supply gap and unlock additional market potential in the Shunter and Mainline Locomotive segment. The third suggested R & I project can close the hydrogen storage specific technology gaps through an integrated technology development project for optimised hydrogen storage systems for use in FCH rail applications. This project could generate new engineering concepts for storing more energy in the available space or evaluate the optimised supply pressure of hydrogen in relation to the hydrogen supply chain, for instance.

Fuel cell and hydrogen technology have significant potential to decarbonise the remainder of diesel-powered rail transportation. Completion of the described technology development and demonstration projects will increase product availability, unlock commercial efficiencies and disperse FCH rail application specific knowledge. In doing so, the R & I projects will pave the way for a smooth and accelerated roll-out of the FCH technology in the rail environment and ensure that quieter, cleaner and versatile transport options replace the remaining diesel fleets.

[11] The exact percentage split between public and private funding sources is to be decided at a later stage.

Document Overview

'Study on the use of fuel cells and hydrogen in the railway environment'

The study is commissioned by the Shift2Rail Joint Undertaking and the Fuel Cells and Hydrogen Joint Undertaking. It consists of three reports and a Final Study:

'Study on the use of fuel cells & hydrogen in the railway environment'

Report 1: *'State of the art and business case and market potential'*

The report provides an overview of past studies or technological trials on the implementation of fuel cell and hydrogen technologies in the railway sector. 22 trials and demonstrations in 14 countries across Europe, Asia, North America, the Middle East, Africa and the Caribbean since 2005 are identified and analysed. Furthermore, the report sheds light on the business cases for FCH rail applications and assesses the market potential to replace diesel-powered trains in Europe by 2030. The analysis for the three focus applications, Multiple Units, Shunters and Mainline Locomotives, concludes that there is significant potential to decarbonise the remainder of the rail sector.

Report 2: *'Analysis of boundary conditions for potential hydrogen rail applications of selected case studies in Europe'*

The report evaluates the economic potential of fuel cell and hydrogen technologies in the EU rail sector based on 10 case studies covering the three focus applications Multiple Units, Shunters and Mainline Locomotives, in nine European countries. The analysis demonstrates that the FCH technology can be economically and environmentally competitive with other powertrain technologies in the rail sector. Additionally, a set of focus topics is provided to introduce key success factors for a successful implementation of the FCH technology in the rail industry.

Report 3: *'Overcoming technological and non-technological barriers to widespread use of FCH in rail applications – recommendations on future R & I'*

The report analyses technological and non-technological barriers that hinder the mass market introduction of the FCH technology in the rail sector. 31 barriers (21 technological and 10 non-technological) are identified, described in detail and prioritised according to their impact on and importance for FCH technology application in the rail sector. The report provides recommendations on three R & I projects to address the identified barriers and realise further optimisation.

All reports are available in electronic format on the FCH JU and S2R JU websites.

Access to reports via FCH JU

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